

DESIGNING MICROELECTROMECHANICAL SYSTEMS-ON-A-CHIP IN A 5-LEVEL SURFACE MICROMACHINE TECHNOLOGY

M. Steven Rodgers and Jeffry J. Sniegowski

Sandia National Laboratories
Intelligent Micromachine Department
MS 1080, P. O. Box 5800
Albuquerque, New Mexico 87185-1080
<http://www.mdl.sandia.gov/Micromachine>

ABSTRACT

A new 5-level polysilicon surface micromachine process has been developed that offers significantly increased system complexity, while further promoting the manufacturability and reliability of microscopic mechanical systems [1,2]. In general, as complexity increases, reliability suffers. This is not necessarily the case, however, with MicroElectroMechanical Systems (MEMS). In fact, utilizing additional levels of polysilicon in structures can greatly increase yield, reliability, and robustness. Surface micromachine devices are built thousands at a time using the infrastructure developed to support the incredibly reliable microelectronics industry, and the batch fabrication process utilized in the 5-level technology further increases reliability and reduces cost by totally eliminating post assembly.

KEYWORDS

Microelectromechanical systems, MEMS, Micromachines, Actuators

1. Introduction

Almost all of today's surface micromachine components are designed for and fabricated in technologies that incorporate three or fewer levels of structural material [3]. The levels are typically deposited as thin films of polysilicon that are on the order of 1 to 2 microns thick. These films are separated by air gaps that are initially defined by thin layers of sacrificial silicon dioxide (commonly referred to as simply "oxide") that are about the same thickness. Other MEMS devices are designed for bulk micromachine processing which typically allows for the definition of only a single layer of structural material, but this one layer can be tens of microns thick. In general, the more layers of structural material that a designer has to work with, the more complicated the device that can be fabricated[2]. Therefore, surface micromachined components tend to have greater functionality than bulk micromachined parts. The bulk micromachined devices, however, are considered in many cases to be more robust since they are less subject to the surface tension forces that act upon all MEMS devices during the final release steps.

A 5-level polysilicon surface micromachine process that incorporates 4 layers of structural films plus an electrical interconnect layer has recently been demonstrated [1]. The main reason for developing this technology was to obtain the functionality that only a 5 or more level process could offer [2]. A major side benefit, however, is that full utilization of all the mechanical levels can significantly increase the performance and robustness of actuation assemblies [4]. In short, this technology provides a base for designing truly sophisticated multi-level microelectromechanical systems, while simultaneously offering much of the yield and robustness that is typically associated with a single-level bulk micromachining technology.

2. The Technology

A n -level technology typically has “ $n-1$ ” levels of sacrificial and structural film pairs deposited above a thin electrical interconnect layer that usually serves as a ground plane. Most of the moving components within a system are electrically biased at the same potential as the ground plane to prevent any undesired electrostatic attraction between the levels. Therefore, a 2-level polysilicon process has only 1 layer of structural material, with the other level defining the ground plane. Such a technology is useful for fabricating simple sensors and actuators (Figure 1a). With 3 levels it is possible to create gears with hubs (Figure 1b). Since surface micromachining technology is so close to being 2-dimensional, it is desirable to fabricate the gear teeth out of both structural levels of material to increase thickness and help prevent meshing gears from riding over each other. A 4-level technology provides an additional layer of material that can be used to define linkage arms that move above the plane of the gears to enable continuous 360° rotation (Figure 1c) [5]. The 5-level technology presented here expands on this progression of functionality to permit complex moveable components to be fabricated on translatable stages that can engage and interact with other subassemblies (Figure 2).

This advanced technology is referred to as SUMMiT V (Sandia Ultra-planar Multi-level MEMS Technology V), and it defines the stack of polysilicon films shown in Figure 3. Each of these film depositions is very conformal, and any topography that is generated gets propagated to all successive layers. Thus, the base topography of any given

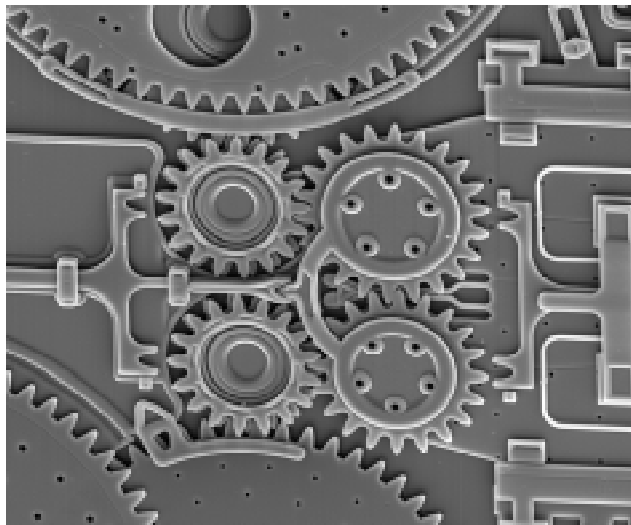
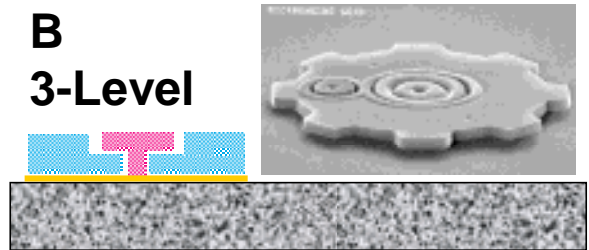


Figure 2. A 5-level technology permits complex interactions to occur between components. The two gears to the right of photo center were fabricated on a moveable stage that has been inserted to complete this train of gears.

A 2-Level



B 3-Level



C 4-Level

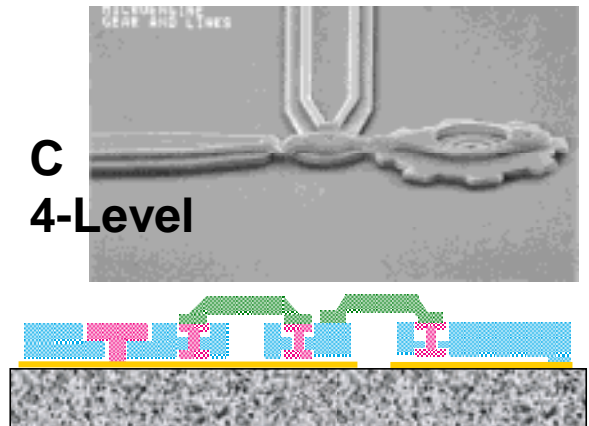


Figure 1. As the number of fabrication levels increases, so does the functionality of the components that can be defined.

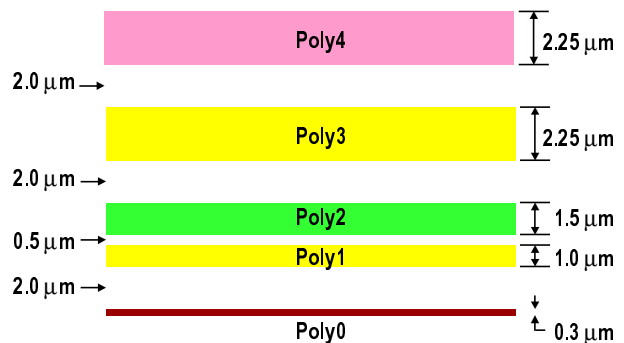


Figure 3. Diagram of 5-level fabrication stack. Shaded areas represent the polysilicon levels, while the clear spaces between them represent the sacrificial silicon dioxide films.

layer is the culmination of the topography generated by the patterning of all of the underlying films. This creates mechanical parasitics that can significantly constrain design flexibility [4]. The linkage arm that connects to the gear in Figure 4 is a prime example. If the design does not account for this protrusion, it could easily collide with the teeth and prevent rotation of the gear.

Planarizing each oxide layer prior to depositing the next polysilicon layer can eliminate these processing artifacts [6], and in SUMMiT V the sacrificial films beneath poly3 and poly4 are both planarized. These steps eliminate most of the issues associated with the underlying topography and greatly simplify the rules for designing in the two upper levels of this process. One side effect, however, is that planarization makes it difficult to allow oxide cuts immediately above and below a polysilicon layer to coincide. Cuts through the oxide layers are made in specific areas in order to connect the polysilicon that will be deposited over a given oxide layer to the polysilicon already beneath the oxide. With planarization, these cuts need to be staggered. This gives rise to the checkerboard texture that can be seen at the top of Figure 5.

Also note the small dark squares in the foreground of Figure 5. These and many of the other openings or holes that are fabricated in this complex 5-level structure are to provide a path for the etchant to flow through the assembly and etch away the layers of sacrificial oxide. Unlike the oxide cuts, the etch release holes between adjacent layers should be coincident or nearly coincident to minimize the etch path. In this 5-level technology, the vertical etch path may be as long or even longer than the lateral etch path.

As system complexity increases, the yield and reliability of each individual component must be very high in order to have appreciable yield of the entire system. Fortunately, the 5-level technology simultaneously offers complexity, performance, and robustness. Even actuation systems that can be defined in a 2-level technology can realize substantial benefits by utilizing all of the structural films available [4]. For example, the force obtainable from an electrostatic actuator is roughly proportional to its area and directly proportional to its thickness. By defining the actuation elements in each structural level and layering them on top of each other as in Figure 6, the force per unit area can be greatly increased. Since the cost of fabricating a device in a given technology varies linearly with the area consumed, this approach has economic benefit as well. The big gain, however, comes from doing the same thing with the actuator support springs (Figure 7). In this case, the z-axis or out of plane stiffness varies as the cube of the spring thickness. This dramatically increases robustness and is of particular importance during the final release process where the surface tension of the etchant acts to pull the actuator down to the underlying ground plane. The additional stiffness prevents this from occurring, reducing adhesion and increasing yield.

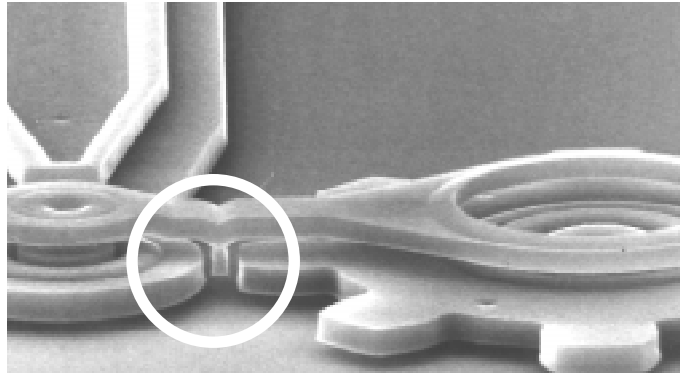


Figure 4. Film protrusions like this one are artifacts of the fabrication technology that are overcome by planarization, enhancing design flexibility.

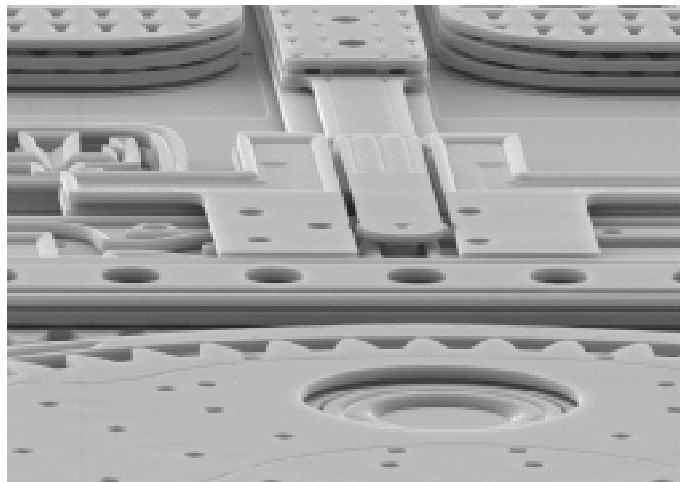


Figure 5. Dark squares at top of photo are depressions in the polysilicon caused by cuts in the underlying oxide. Dark squares in the gear up front are etch release holes that provide a path for etchant flow.

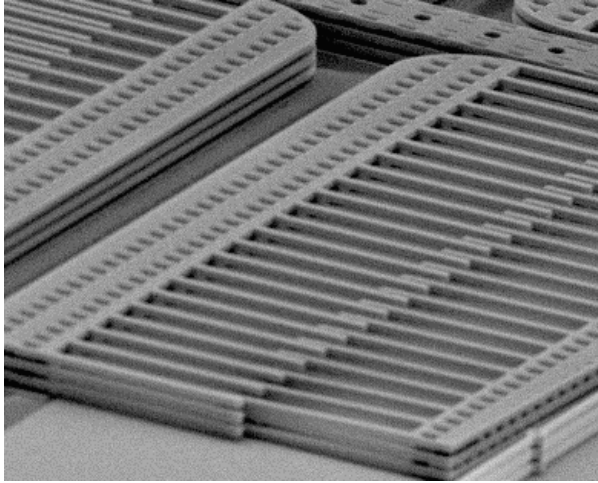


Figure 6. Actuator drive force can be substantially increased by utilizing all available layers.

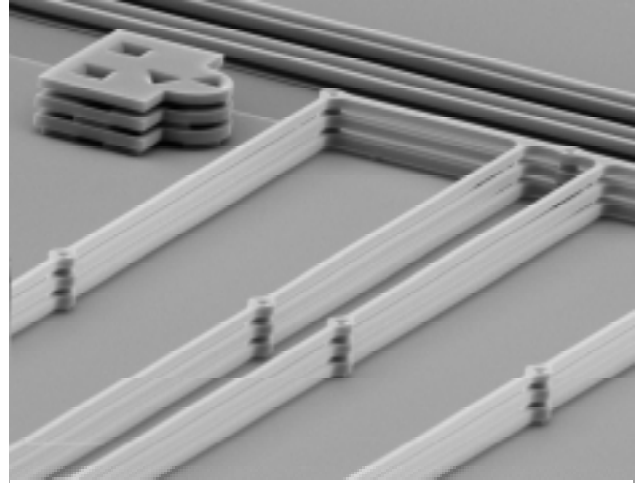


Figure 7. Utilizing all of the layers in this support spring dramatically increases its z-axis stiffness.

3. Summary

It is not uncommon in the engineering world to make trade-offs or to compromise optimization of one parameter at the expense of another. For example, increased complexity normally means reduced reliability. The 5-level process presented here provides a technology base for designing microelectromechanical systems with complexity on a scale that was previously unrealizable. Yet, the yields so far have been the highest we have seen at Sandia National Laboratories for any MEMS technology, and it provides a strong foundation from which to establish a commercial process.

4. Acknowledgements

The authors are grateful to Michael Callahan for funding this work, the personnel of the Microelectronics Development Laboratory at Sandia National Laboratories (SNL) for fabricating the devices, and to Gary Zender of SNL for the SEM images. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under contract DE-AC04-94AL85000.

REFERENCES

1. J. J. Sniegowski and M. S. Rodgers, "Multi-layer enhancement to polysilicon surface-micromachining technology," IEDM97, Washington DC, 12/7-10/97, (1997) pp. 903-906.
2. M. S. Rodgers and J. J. Sniegowski, "5-Level Polysilicon Surface Micromachine Technology: Application to Complex Mechanical System", Accepted for publication Technical Digest of the 1998 Solid State Sensor and Actuator Workshop, Hilton Head Island, SC, 6/98.
3. Information on other technologies can be found at <http://www.mdl.sandia.gov/Micromachine/links.html>
4. M. S. Rodgers, J. J. Sniegowski, S. L. Miller, C. C. Barron, and P. J. McWhorter, "Advanced micromechanisms in a multi-level polysilicon technology", Proc. of SPIE Micromachined Devices and Components III, 3224, 9/29/97, Austin, TX, pp. 120-130, 1997.
5. E. J. Garcia and J. J. Sniegowski, "Surface Micromachined Microengine", Sensors and Actuators A, 48, p. 203, 1995.
6. R. D. Nasby, J. J. Sniegowski, J. H. Smith, S. Montague, C. C. Barron, W. P. Eaton, P. J. McWhorter, D. L. Hetherington, C. A. Apblett, and J. G. Fleming, "Application of Chemical-Mechanical Polishing to Planarization of Surface Micromachined Devices", Technical Digest of the 1996 Solid State Sensor and Actuator Workshop, Hilton Head Island, SC, 6/3-6/96, (1996) pp.48-53.